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6. AUTHOR(S)
Sarah Gibson

Yuhong Fan
K. D. Leka

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NCAR/HAO
p.o. box 3000
Boulder, CO
80307-3000

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2. A numerical model of dynamic magnetic flux emergence (*Manchester et al., 2004; Fan, 2004*).
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4. An analytic flux rope model (*Gibson et al., 2002*) allowing parameterized studies of magnetic free energy
5. Tests of standard observational analysis techniques such as helicity injection (*Gibson et al., 2004*), inference of magnetic twist (*Leka et al., 2005*), and coronal field extrapolations (*Barnes et al., 2005a; 2005b*).
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7. A comparison of flux rope simulations with sigmoid evolution, including the demonstration of partially erupting flux ropes

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Emergence of Twisted Magnetic Flux into the Corona

P.I. Sarah Gibson
High Altitude Observatory, National Center for Atmospheric Research, Boulder, CO, 80307-3000

July, 2005

Summary of Effort

The overall goal of this proposal has been to describe the emergence, evolution, and eruption of magnetic flux ropes in the corona. The following achievements are noted:

1. A numerical model of magnetic flux emergence (*Fan and Gibson, 2003;2004; Fan, 2005*), demonstrating both flux rope equilibria and instabilities leading to eruptions.
2. A numerical model of dynamic magnetic flux emergence (*Manchester et al., 2004; Fan, 2004*).
3. A comparison of model predictions to CME precursor observations, including X-ray sigmoids and associated filaments, and rotating sunspots (*Gibson et al., 2004; 2005a*), and a comprehensive observational analysis of white light cavities in quiescent streamers (*Gibson et al., 2005b*).
4. An analytic flux rope model (*Gibson et al., 2002*) allowing parameterized studies of magnetic free energy (*Jain et al., in preparation)*
5. Tests of standard observational analysis techniques such as helicity injection (*Gibson et al., 2004*), inference of magnetic twist (*Leka et al., 2005*), and coronal field extrapolations (*Barnes et al., 2005a; 2005b*).
6. A comparison of equilibrium states, eruptive properties and observables for 3D vs. 2D models (*Fan and Gibson, 2005*)
7. A comparison of flux rope simulations with sigmoid evolution, including the demonstration of partially erupting flux ropes (*Gibson et al., 2005a*).

Accomplishments

Research Highlights:

1. Sigmoid numerical model

A major accomplishment of this study was the development of a sigmoid numerical model (from here on SNM) (*Fan and Gibson, 2003*; *2004*). In this numerical model, 3D MHD simulations of the emergence of a twisted magnetic flux rope into a pre-existing coronal potential magnetic arcade were carried out. The motivation was to investigate the dynamic evolution of a coronal magnetic field in response to the emergence of significantly twisted structures, and to understand the nature of observed X-ray sigmoids (*Canfield et al., 2000*). In these MHD simulations, the treatment of the energy equation and the thermodynamics of the coronal plasma were drastically simplified by using an isothermal equation of state. The focus was the evolution of the coronal magnetic field under the conditions of high electric conductivity and low plasma β. The simulations showed that the line-tied emerging flux rope became kink unstable when a sufficient amount of twist was transported into the corona. For an emerging rope with a left-handed twist (which is the preferred sense of twist for active regions in the northern hemisphere), the writhing of the tube resulting from the kink instability was also left-handed, producing a forward S-shape for the rope axis as viewed from the top, opposite to the inverse S-shaped X-ray sigmoid morphology preferentially seen in the northern hemisphere. However it was found that the writhing motion of the rope and its interaction with the ambient coronal magnetic field also drove the formation of an intense current layer, which displayed an inverse S-shape, consistent with the morphology of X-ray sigmoids (Figure 1).

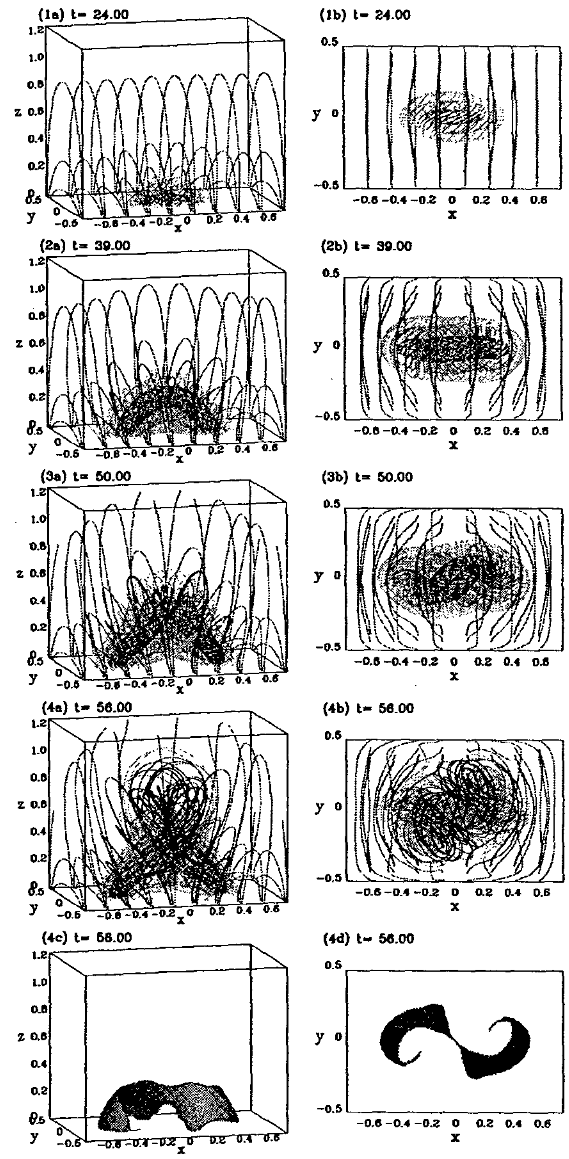

Fig 1. Panels [1a]-[4a] and [1b]-[4b] show the 3D evolution of the coronal magnetic field, when driven at the lower boundary by the emergence of a twisted flux rope into an overlying coronal arcade (red field lines). Field lines in the rope are color-coded based on the flux surfaces of the initial rope they belong to. When the emerged rope became substantially kinked (panels [4a] and [4b]), a curved layer of highly concentrated current formed an inverse-S shape as viewed from the top (panels [4c] and [4d]). (From *Fan and Gibson, 2003*).

Fan and Gibson (*2004*) further presented results of a simulation where a rope with less twist was emerged – in this case, a force-free equilibrium without any eruption was found. The evolution of relative magnetic helicity for the two cases was compared, demonstrating the likelihood of a critical amount of twist leading to instability and eruption. In this paper, a comparison of simulations with different numerical grid resolution showed that the current density in the inverse-S shaped current layer increased linearly with resolution, indicating that the current layer was consistent with being a current sheet limited by numerical resolution. Finally, the paper considered a simulation run where the orientation of the overlying arcade relative to the flux rope was reversed. In this case reconnection between the two systems occurred as the rope emerged and there was no longer an initial quasi-static stage which allowed a twisted rope to exist within the coronal arcade. No eruption was obtained since the free magnetic energy associated with the twisted emerging flux was dissipated as it was transported into the corona. Thus, the relative orientations of emerging magnetic flux and pre-existing coronal flux could be crucial to the storage of free magnetic energy and the buildup of a precursor structure for eruption.

Fan (*2005*) extended SNM to full spherical geometry, so as to address the question of magnetic energy storage and release in coronal mass ejections. In an earlier study, Sturrock et al. (*2001*) considered a 3D coronal magnetic field that consisted of a twisted magnetic flux rope anchored at both ends, confined within an external potential arcade, as a possible configuration for CME precursors. Through an order of magnitude estimate they found that with a moderate amount of total twist (less than 2 full field line winds), the free magnetic energy associated with the twisted magnetic flux rope was sufficient for the flux rope to rupture through the arcade and extend to infinity as a CME, without opening up all the arcade field. Fan (*2005*) modeled this dynamic scenario by performing isothermal MHD simulations in the low-β regime of the evolution of the coronal magnetic field as a twisted, line-tied magnetic flux rope was transported slowly into the corona previously occupied by a potential arcade field. The simulations showed two distinct phases for the evolution of the coronal magnetic field. In the earlier phase, the coronal flux rope evolved quasi-statically with both the magnetic energy and twist being built up as a result of flux emergence. When sufficient twist and magnetic energy were transported into the corona, the flux rope underwent a significant acceleration and was able to rupture through the overlying arcade, producing a CME-like eruption. In this latter dynamic phase of the evolution, the flux rope became kinked, which facilitated the loss of confinement of the flux rope by changing its orientation at the apex such that it became easier for the flux rope to part and erupt through the arcade field.

2. Dynamic flux emergence through the photosphere

The SNM model imposed a kinematic emergence of a flux rope at the lower boundary representing the "photosphere", and calculated the dynamic evolution of the coronal field as the rope emerged. The time variation of the lower boundary field was prescribed to be consistent with the bodily emergence of a flux rope. Many important dynamic effects including the effects of gravity as the rope moved from the dense solar interior into the solar atmosphere could not be captured in such a kinematic boundary representation. In a parallel effort to the SNM analysis, Manchester et al. (*2004*) addressed the dynamic process of magnetic flux emergence across the solar photosphere (see also *Fan 2004*). Using the BATS-R-US code, a 3D MHD code with adaptive mesh refinement developed at U of Michigan, Manchester et al. (*2004*) quantitatively reproduced the results of an earlier simulation of *Fan (2001)*, which used a modified Zeus-3D MHD code. In addition simulations were performed with different lengths for the buoyant segment of the initial flux rope leading to the finding that the dynamics of flux emergence through the photosphere depended sensitively on the number of field line winds that was contained in the emerging segment of the rope. In the earlier case of *Fan (2001)*, the emerging portion contained about 3 field line rotations or winds, and mass that drained down along the emerged field lines was trapped at the bottom of the winds, preventing the bottom mass-laden part of the emerging rope cross-section from getting significantly above the photosphere. However, in the new case where the emerging segment contained about 1.5 field line winds, it was found that the upper part of the flux rope drained more effectively and rose buoyantly, so much so that it began to separate from the lower, mass-laden part. The separation occurred by stretching the field, which formed a sigmoid current sheet where reconnection severed the field lines to form a new system of closed flux (Figure 2). This flux then erupted into the corona with maximum speed of 5 (a_s), where (a_s) is the photosphere sound speed of 6.5 km/s. Essential to the eruption process were shearing motions driven by the Lorentz force which naturally occurred as the rope expanded in the pressure stratified atmosphere. The shearing motions transported axial flux and energy to the expanding portion of the magnetic field, which further drove the eruption. Once the axial flux was largely transported from the submerged field, the expansion of the magnetic field in the corona began to decelerate. This simulation confirmed, in fully 3D geometry, the eruption process suggested by *Manchester (2000)* that was based on simpler 2D simulations.

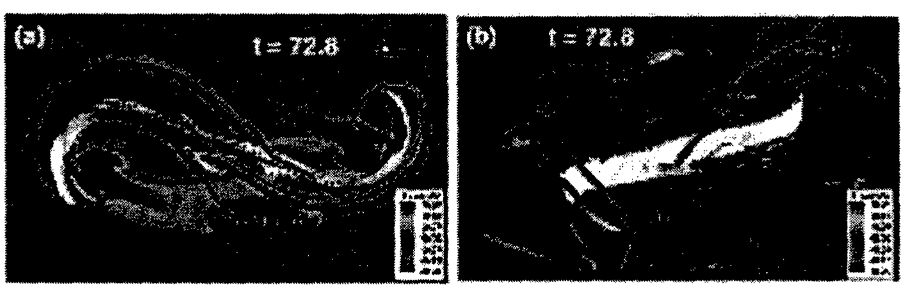

Fig. 2.— Structure of the electric current density illustrated with a three-dimensional, shaded isosurface at value j 1/4 0:01Bph=Hph. The magnetic field is depicted with black and magenta lines, which lie close to the current sheet. A color image shows the magnitude Bz at the photosphere (z 1/4 0). The system is shown at t 1/4 72:8, at which time much of the magnetic flux has reconnected at the current sheet, forming the flux rope high in the corona. (From Manchester et al. (*2004*)).

3. Observable properties of flux rope

The main, erupting SNM simulation described in Fan and Gibson (*2003; 2004*) was the subject of a detailed study on the observable properties of a magnetic flux rope in the corona (*Gibson et al.*, 2004). In particular, the structure, evolution, and relative location and orientation of S-shaped, or sigmoid active regions and filaments were compared to topological features of the magnetic flux rope, testing the theories that 1) X-ray sigmoids appear at the regions of the flux rope known as bald patch-associated separatrix surfaces (BPSS), where, under dynamic forcing, current sheets can form leading to reconnection and localized heating (Figure 3), and that 2) filaments are regions of enhanced density contained within dips in the magnetic flux rope (Figure 4). The shapes and relative orientations and locations of the BPSS and dipped field in the emerging flux rope were consistent with observations of X-ray sigmoids and their associated filaments. Moreover, current layers indeed formed along the sigmoid BPSS as the flux rope was driven by the kink instability, which is evidence for the theory that X-ray sigmoids appear when this critical topological surface is dynamically forced.

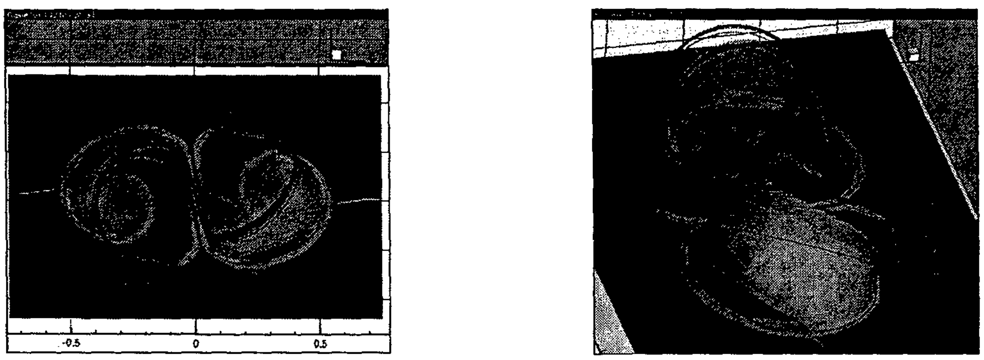

Fig 3. Comparison of Fan and Gibson (*2004*) t=56 BPSS (red field lines) to current sheets (yellowish-green isosurfaces). (left – top view, right – front view). Color contours at bottom boundary represent magnitude of current at photosphere (same color scaling as coronal isosurfaces).

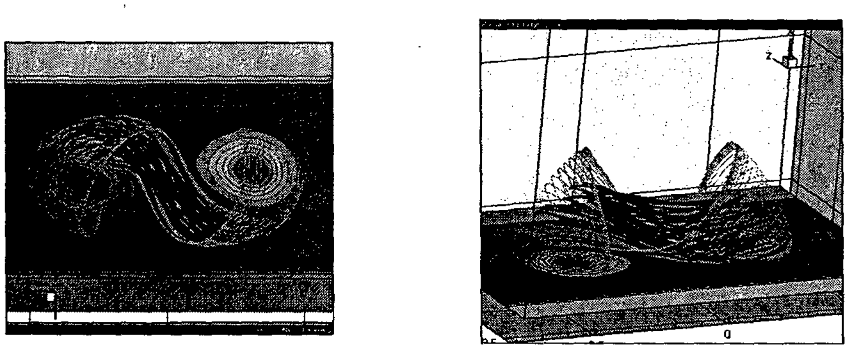

Fig 4. (left) Comparison of Fan and Gibson (*2004*) t=39 BPSS (purple field lines) to dipped field likely to contain filament material (brown). (left – top view, right – side view). Color contours at bottom boundary represent magnitude of normal magnetic field at photosphere (red is positive, blue is negative).

An issue of current debate is whether or not magnetic flux ropes are present in the corona prior to the CME, or whether they are formed during eruptions. This is important to establish because a flux rope precursor is a reservoir of magnetic energy, so observations that can be clearly associated with a flux rope are strong indicators for eruption. The analysis presented in Gibson et al. (*2004*) supported the premise of flux rope precursors, since the model filament present during the non-eruptive portion of the rope's emergence matched observations of quiescent coronal regions, as did the BPSS sigmoid. Gibson et al. (*2005a*) discussed how current sheets could form on this BPSS not only during the actual eruption, but also during noneruptive instabilities and when driven by emerging flux as described in Manchester et al. (*2004*). Intermittent X-ray sigmoids observed for days before an eruption are thus evidence for the existence of a pre-CME flux rope.

Another class of flux rope precursors are white light coronal cavities. CMEs are well-known to often possess three parts, a front, a cavity, and a bright core. Observations of the low solar corona (e.g. those taken by the HAO Mauna Loa Solar Observatory Mark IV coronameter (Mk4)) demonstrate that this three-part structure can be present well before the eruption, as a helmet streamer, embedded white light cavity, and prominence core (Figure 5). Magnetic flux rope models provide a physical explanation for the cavity, forming a region of depleted density surrounding the prominence core (*Low and Hundhausen, 1995*). Indeed, in the SNM model a depleted density region can be identified with the flux rope. The quiescent cavities observed in white light are thus consistent with a precursor magnetic flux rope in the corona. Gibson et al. (*2005b*) presented the first comprehensive, quantitative analysis of white light quiescent cavities as observed by the Mk4 coronameter. They found that such cavities were ubiquitous, and for those associated with polar crown filaments, often stable for days and even weeks at a time; indeed identifiable as long-lived systems that survived for months. The maximum density depletion found in a cavity (relative to its surrounding streamer) was 43%, and in general cavity depletion decreased with height, indicating that the density in cavities may drop off more slowly within cavities than in surrounding streamers. Multiple cases were found where quiescent cavities directly erupted into CMEs, with those associated with active regions being generally smaller and faster than those associated with polar crown filaments. Finally, Gibson et al. (*2005b*) found that although the cavities were actually quite stable structures, their evolution just prior to the CME, including a necking off at the cavity bottom, the rising of associated filaments, and possibly a more sharply defined boundary, could be useful for indicating when a region was about to erupt. More importantly, perhaps, it provides insight into the physics behind the eruption, which is ultimately the best route to significant improvements in CME prediction.

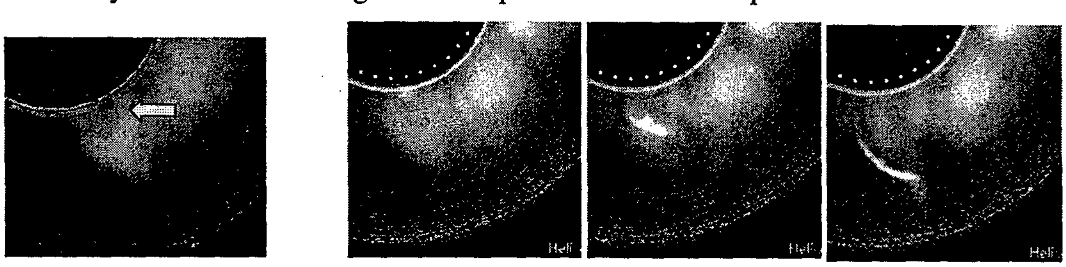

Fig 5. (left) Mauna Loa Mk4 white light coronagraph image showing quiescent cavity: November 18, 1999. (right three images) CME eruption of cavity, November 19, 1999.

4. Analytic flux rope model and magnetic free energy

Analytic models are useful alternatives to numerical simulations, as they facilitate parameter studies and the exact calculation of interesting physical properties. Gibson et al. *(2002)* presented a simple 3D analytic model of a spheroidal flux rope (Sigmoid Analytic Model, or SAM). This model provided a good deal of insight into the three-dimensional nature of magnetic flux ropes, and was useful in the development of techniques to pin down the observable properties of such flux ropes which were ultimately applied to the SNM models. This model was also of interest because it allowed a determination of the degree to which a flux rope possessed free magnetic energy. Free magnetic energy is the difference between the energy in the (non-potential) model and the energy of a potential field configuration corresponding to the same boundary condition at the photosphere. The free magnetic energy is a critical indicator of the amount of energy that can be released in a CME. In order to determine a potential field configuration with the same boundary condition as the non-potential SAM field, it was necessary to solve Laplace's equation in oblate spheroidal geometry with proper boundary conditions and to compute special functions (e.g. complex associated Legendre functions and Gamma functions) to determine a set of parameters. By calculating the magnetic energy difference between the two systems, free energy can be specified, which is indicative of the energy that can be released in a CME. A parameter study then is possible for investigating how properties such as magnetic field strength, region size, and degree of magnetic twist affect free energy (*Jain et al., in preparation*).

5. Testing photospheric field analysis techniques

As long as regular measurements of the coronal magnetic field are not available, its true nature is largely based on speculation. The approach largely presented here has been to use theoretical models of the magnetic field, with indirect evidence of the field structure provided by coronal plasma observations. Another approach is to use the photospheric magnetic field, which is well-observed, to extrapolate or otherwise gain information about the evolving coronal magnetic field. A range of techniques that use the photospheric field in this manner have been developed: these can be directly tested by using the lower boundary condition of SNM as proxy for the photospheric field, and then comparing resulting predictions to properties of the, *a priori* known, SNM coronal field.

Gibson *et al.*, (2004) considered how apparent horizontal motions of magnetic elements at the photosphere caused by the emerging flux rope might be interpreted. In particular, it was shown that local correlation tracking (LCT) analysis (*Welsch et al., 2004*) of a time-series of magnetograms for SNM led to an underestimate of the amount of magnetic helicity transported into the corona by the flux rope, largely because of undetectable twisting motions along the magnetic flux surfaces. High-resolution observations of rotating sunspots could provide better information about such rotational motions, and it was shown by considering the separated flux rope legs as proxies for fully formed sunspots, that the amount of rotation that would be observed before the region became kink unstable would be in the range 40-200 degrees per leg/sunspot, consistent with observations (*Brown et al., 2003*). However, this amount of observed rotation was again well short of the total amount of twist carried into the corona by the flux rope, and in general the analysis indicated that using photospheric motions to determine helicity injection was prone to significant underestimation, at least to the extent such injection arises from emerging twisted fields. This is important because estimates of helicity input to the corona have been used to quantify its energetic state, and, on longer time-frames, to estimate the source term of the "helicity budget" which traces magnetic twist from emergence all the way out to magnetic clouds observed passing the Earth.

Barnes et al. (*2005b*) considered the technique of extrapolating the coronal field from photospheric observations, using the SNM as well as another analytic model field configuration (*Chou and Low, 1994*) as proxy photospheric fields. The presence, location, size and shape of separatrix surfaces and layers as well as X –type separators were considered in determining whether extrapolations, both linear and nonlinear force-free, did a good job of reproducing the model field. A quantitative measure for goodness of extrapolation was developed which took into account the divergence of extrapolated magnetic field lines from the actual model field lines. The conclusion was that the extrapolation techniques generally failed to reproduce the flux rope field, and that the qualitative comparisons of field lines, and even topological properties such as separatrix surfaces, could be misleading in judging the performance of an extrapolation. The quantitative measure was proposed as a more robust way of assessing the performance of extrapolations when the true solution is known.

Another type of extrapolation technique was implemented by Barnes et al. (*2005a*), namely a Magnetic Charge Topology (MCT) model. This technique represents the photospheric magnetic flux distribution as a collection of point charges at or below the photosphere, from which the coronal field is uniquely defined. The topology of the coronal magnetic field was thus neatly determined by the existence of separatrix surfaces, which enclose flux domains connecting distinct charges. In its minimum energy state, the magnetic field in the corona is a potential field everywhere except along separator field lines, defined as the intersection between separatrix surfaces, where currents can flow. The model can be used to estimate rates of flux emergence/submergence and reconnection, as well as photospheric velocities. Barnes et al. (*2005a*) discussed in detail how to implement such a model for a time series of vector magnetograms, paying particular attention to distinguishing real evolution of the photospheric magnetic flux from changes due to variations in atmospheric seeing, as well as uncorrelated noise. They determined the reliability of the method and estimated the uncertainties in its results. They then demonstrated it through an application to NOAA active region 8210, which has been the subject of extensive previous study, and of great interest to our MURI collaborators.

Leka et al. (*2005*) examined the question of whether there is sufficient magnetic twist in solar active regions for the onset of the kink instability using a "blind test" of analysis methods commonly used to interpret observational data. Proxy magnetograms were constructed from SNM. The calculation of the best-fit linear force-free parameter α_{best}

was applied, with the goal of recovering the model input helicity. For this simple magnetic structure, three effects combined to produce an underestimation of the known helicity: (1) the influence of horizontal fields with lower local α values within the flux rope; (2) an assumed simple relation between α_{best} and the winding rate q which did not apply to nonaxis fields in a flux rope that was not thin; and (3) the difficulty in interpreting the force-free twist parameter measured for a field that was *forced.* A different method to evaluate the magnetic twist in active region flux ropes was presented, which was based on evaluating the peak α value at the flux rope axis. When applied to SNM data, the twist component of the magnetic helicity was essentially recovered. Both the α_{best} and the new α_{peak} methods were then applied to observational photospheric vector magnetic field data of NOAA AR 7201 (Figure 6). The α_{best} approach was then confounded further in NOAA AR 7201 by a distribution of a that contained both signs, as is generally observed in active regions. The result from the proposed α_{peak} approach suggests that a larger magnetic twist is present in this active region's -spot than would have been inferred from α_{best}, by at least a factor of 3. The magnetic fields in localized active region flux ropes thus may indeed carry greater than 2π winds, and thus the kink instability is a possible trigger mechanism for solar flares and coronal mass ejections.

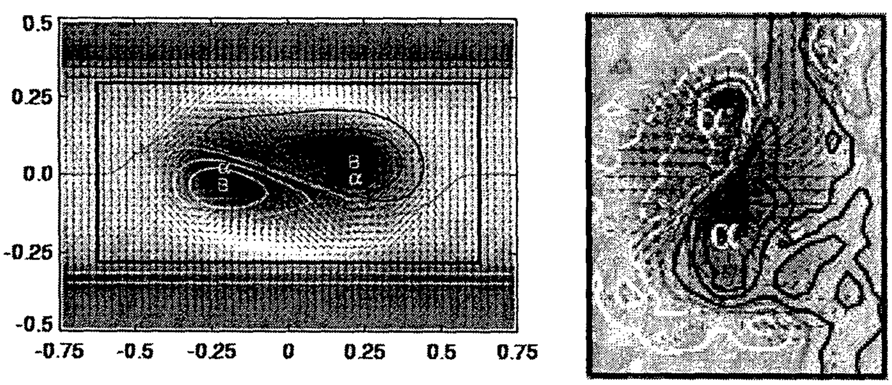

Fig 6. (left)Vector magnetic field at z =0.006 L, timestep 30, from the numerical simulation of Fan and Gibson (*2004*). Underlying ``continuum image" is a reverse-color image of B^2; Positive/negative vertical magnetic flux is indicated by white/black contours at 100,~500,~1000,~2000 G, and the magnetic neutral lines are also indicated by the thicker grey contour. Horizontal magnetic field is plotted at every 4th pixel. Tickmarks are in units of L. The peak Bz locations are marked with "B"s, the locations of peak α are marked with "α"s. The locations of α_{peak} coincide with the known fluxrope axis locations (to within the size of the α). (right) Continuum image of the emerging δ region in NOAA AR 7201 observed 1992 June 19 with the NSO/HAO Advanced Stokes Polarimeter. Tick marks are approximately in Mm. α s indicate the locations of α_{peak}.

6. 2D vs. 3D flux rope models

Fan and Gibson (*2005*) presented a comparison of the SNM model to a more simple, two-dimensional axisymmetric flux rope model. Both MHD simulations modeled the evolution of a twisted magnetic flux rope emerging into the low-β corona previously occupied by a potential arcade field. Both simulations showed two distinct stages of evolution.

The earlier evolution was quasistatic during which if the flux emergence were stopped, the flux rope settled to a neighboring equilibrium with stored free magnetic energy. For these partially emerged flux ropes, current sheets could develop along the BPSS, due to the different dynamic behaviors between the fully emerged twisted field lines and the anchored arcade-like field lines. It has been discussed above how current sheets formed at the sigmoid BPSS of the SNM simulations; in the case of a partially-emerged, 2D-axisymmetric-toroidal flux rope, the BPSS within the flux rope had the shape of a long tunnel enclosing the prominence material supported by the field line dips. Current sheet formation along the BPSS in this case could explain the limb observation of a circular X-ray structure surrounding the filament inside a stable filament cavity (the so-called "chewy nougat", see e.g. Hudson et al. (*1999*)).

The second stage of evolution, i.e. the loss of equilibrium of the flux rope, was found for both the 2D flux rope and the 3D (SNM) flux rope, when too much twisted flux had been transported into the corona. In the 2D case, the imposed azimuthal invariance prohibited the kink motion. The entire flux rope erupted with all of the arcade field stretched out with the flux rope. Reconnection took place in the vertical current sheet that formed behind the erupting flux rope, allowing the flux rope to escape. In the 3D case, with the build-up of a moderate amount of twist, the line-tied flux rope kinked and erupted through the arcade field at a localized area, with most of the arcade field remaining closed. A sigmoid-shaped current sheet formed below the flux rope during the eruption, as discussed above.

7. Sigmoid evolution and partially erupting flux ropes

As described above, the flux rope models predict coronal observables, including heating along forward or inverse S-shaped, or sigmoid, topological surfaces. Gibson et al. (*2005a*) used the spherical SNM model of Fan (*2005*) and the analysis of Manchester et al. (*2004*), as well as the numerical simulations of Toeroek et al. (*2004*) and Kliem et al. (*2004*) to demonstrate that the observed evolution of such sigmoids prior to, during, and after eruption was consistent with the presence of a long-lived coronal magnetic flux rope. Before CMEs, they found that the appearance of sigmoids as general brightenings possessing an S or inverse-S pattern was consistent with the more-or-less continuous dynamic perturbation of the BPSS field lines as heavy photospheric material dropped down from an emerging rope in an ongoing process of internal reconnections (e.g. see Figure 2). Transient, noneruptive sigmoids could also occur before a CME when, for example, instabilities not leading to an eruption perturbed the rope and caused current-sheet formation along the BPSS or in the vicinity of an X-line. During the CME, transient sigmoids could occur as the rope lost equilibrium and erupted, causing current sheet formation along the BPSS or again at the X-line. After the CME, field lines reconnected into cusped field lines below the erupting portion of the rope in accordance with the observed transition of the eruptive sigmoid into a cusp (Figure 7). The fact that the BPSS remained (Figure 7) implies that the flux rope only partially erupted, allowing a quick return to persistent or transient soft X-ray sigmoids, or indeed eventually to more eruptions. A partially erupting flux rope could also explain partially or non-erupting filaments as are often observed, as well as the presence of hot or mixed temperature charge states within magnetic clouds (*Gloeckler et al., 1999*).

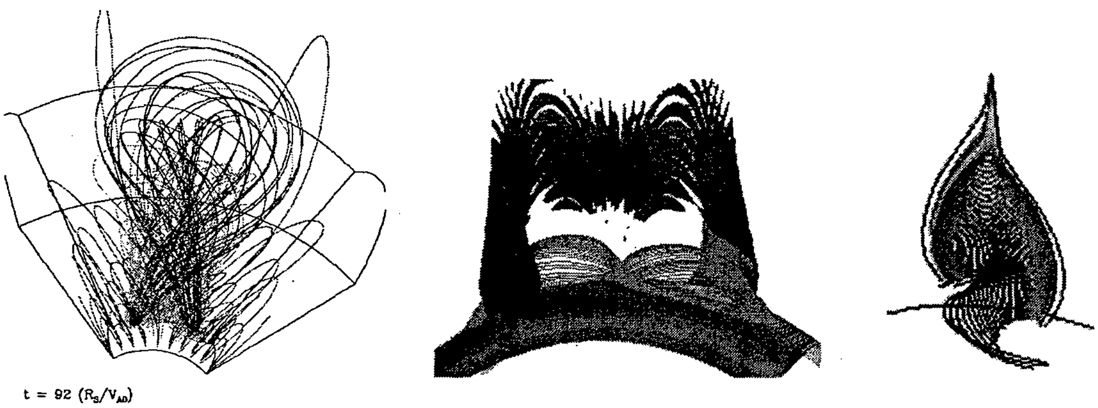

Fig 7. End-states: (left) Erupting SNM-sperical flux rope. (middle) Vertical current sheet forming behind portion of flux rope that escapes. (right) Cusp-shaped field lines reconnecting below erupting rope. Not all of the twisted rope has erupted: a sigmoid BPSS is still present beneath the reconnecting field (middle and right frames)

Significance to the field:

The highly topical theory that magnetic flux ropes are fundamental to CMEs and their precursors has been directly supported by the research described above.

The basic hypothesis that the CME results from the destabilization of a twisted magnetic flux rope, where the twist in the rope provides the energy necessary to drive the CME, has been successfully tested. Both equilibrium and erupting solutions were found in the 2D and 3D numerical models, depending crucially upon the amount of twist transported into the corona. (*Fan and Gibson, 2003; 2004; Fan 2005*)

The emergence of a flux rope into the corona has been demonstrated. This dynamic emergence of the rope past the photosphere was not a smooth process, but rather occurred by a process of internal reconnections that in a sense repeatedly split the rope into two parts, the upper portion of which being the emerged rope. (*Manchester et al., 2004; Fan, 2004*)

The magnetic topology of a flux rope has been shown to explain observational properties, before, during, and after the CME, thus supporting the concept of a long-lived, repeatedly erupting flux rope. Observations of quiescent white light cavities were found to be consistent with the presence of a flux rope prior to eruption, and critical new information about their evolution just prior to eruptions was obtained. Both the numerical and analytic models (SNM and SAM) reproduced observed relationships between coronal filaments (modeled as dipped field lines) and X-ray sigmoids (modeled as dissipative heating at reconnection sites, occurring at separatrix surfaces, e.g. BPSSs), and SNM went one step further by demonstrating that current sheets did in fact form in the region of the BPSS. The BPSS of the 2D axisymmetric model also suggested an intriguing possible analogue to the X-ray sigmoids, i.e. the bright X-ray rings around filament cavities that are sometimes observed. Finally, the fact that the simulated SNM eruption resulted in a portion of the flux rope left behind is highly significant, in that it implies that a flux rope topology is consistent with observations of partially erupting filaments, sigmoid reformation immediately after eruption, white light cavity reformation soon after eruption, and a range of thermal configurations of charge states in magnetic clouds. (*Gibson et al., 2002; 2004; 2005a; 2005b; Fan and Gibson, 2005*).

Lastly, the studies testing observational analysis techniques are critical for helping understand how well fundamental properties of the coronal fields associated with CMEs can be determined from existing observations, using existing methods of analysis. (*Barnes et al., 2005a; 2005b; Gibson et al., 2004; Leka et al., 2005*)

Relationship to original goals:

We have addressed all four of our original objectives with these studies:

First of all we proposed to investigate the interaction of an emerging flux rope with a pre-existing atmosphere, which was directly addressed by the sigmoid numerical model (SNM) (*Fan and Gibson, 2003; 2004; Fan, 2005*). The dynamic properties of such an emergence, not directly addressed by SNM, was also examined (*Manchester et al., 2004; Fan, 2004*), as well as the details of the storage and release of magnetic energy in magnetic flux ropes (*Fan, 2005; Fan and Gibson, 2005)*.

Second, we proposed to consider the topological and reconnection properties of the emerging flux, which we have done by studying the formation of current sheets along the BPSS, both 2D and 3D, as well as the importance of partial eruptions, both during emergence and eruption (*Gibson et al., 2004;2005a; Fan and Gibson, 2005; Manchester et al., 2004*). We have also considered the importance of magnetic topology in the extrapolation of coronal fields (*Barnes et al., 2005a; 2005b*).

Third, we planned to compare equilibrium end-states of numerical models with analytic models developed in a complementary program of research: we have done so with our parallel numerical and analytic models (SNM and SAM), both of which can describe precursor coronal flux rope equilibria (*Gibson et al., 2002; Fan and Gibson, 2003; 2004*). We have also demonstrated that the post-eruption end-state for SNM is non-potential, indeed that it still possesses some portion of a magnetic flux rope (*Gibson et al., 2005a*). This suggests that not all of its free magnetic energy has been tapped (e.g. *Jain et al., in preparation*), so that it is a likely site of future eruptions.

Finally, we have compared, as planned, observables determined from our models to observations of vector magnetic fields (*Leka et al., 2005*), rotating sunspots, and coronal observations of filaments and sigmoids, before, during, and after eruptions (*Gibson et al., 2004; 2005a*). We have also completed a comprehensive observational survey of white light cavities, yielding results consistent with the presence of flux ropes in the corona prior to the CME (*Gibson et al., 2005b*).

Relevance to the Air Force's mission:

The work in this proposal is crucial for understanding the origins and physics of CMEs, which in turn are major components of Space Weather. The Air Force's mission requires information superiority, which is becoming more and more affected by Space Weather.

Potential applications to technology challenges: N/A

Personnel Supported

1. P.I. Sarah Gibson (NCAR/HAO): one month salary total, travel support
2. co-I. Yuhong Fan (NCAR/HAO): travel support
3. co-I K.D. Leka (CoRA/NWRA): funded 25% time salary all three years
4. NCAR/HAO visiting scientist Graham Barnes (CoRA/NWRA): funded 50% time salary for 2.5 years, travel support
5. NCAR/HAO visiting scientist Rekha Jain (University of Sheffield): funded one month salary total, travel support
6. NCAR/HAO visiting scientist David Foster (U. of Colorado, Boulder): funded approximately three months salary total
7. NCAR/HAO associate scientist Andy Stanger (NCAR/HAO): funded approximately three months salary total
8. NCAR/HAO visiting scientist Tibor Toeroek (MSSL, Holmbury St.Mary): travel support
9. NCAR/HAO visiting scientist Dana Longcope (Montana State, Bozeman): travel support
10. NCAR/HAO visiting scientist Ward Manchester (Univ. of Michigan, Ann Arbor): travel support
11. NCAR/HAO visiting scientist Cristina Mandrini, (IAFE, Buenos Aires): travel support
12. Collaborator George Fisher, (UC Berkeley, SSL, Berkeley): travel support
13. Collaborators B. C. Low (NCAR/HAO, Boulder), Bill Abbett, Steve Ledvina, Janet Luhmann (UC Berkeley, SSL, Berkeley), Pascal Demoulin (Meudon Observatory, Paris): no expenditure

Project Publications:

- Barnes, G., Longcope, D. W., and Leka, K. D., 2005a, ApJ, 629, 561
- Barnes, G., Leka, K. D., Wheatland, M., 2005b, *submitted for internal HAO review*
- Fan, Y. 2004, in *The Solar-B Mission and the Forefront of Solar Physics*, ASP Conference Series, Vol. 325, Proceedings of the Fifth Solar-B Science Meeting held 12-14 November, 2003 in Roppongi, Tokyo, Japan. Edited by T. Sakurai and T. Sekii. San Francisco: Astronomical Society of the Pacific, 2004., p.47
- Fan, Y., 2005, ApJ, in press
- Fan, Y., and Gibson S., 2003, ApJ, 589, L108
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- Fan, Y. and Gibson, S., 2005, SOHO 16/Solar Wind 11 Proceedings, *submitted*
- Gibson, S. E., Low, B. C., Leka, K. D., Fan, Y., and Fletcher, L., 2002, IAU 188 conference proceedings, ESA publications
- Gibson, S., Fan, Y., Mandrini, C., Fisher, G., and Demoulin, P., 2004, ApJ, 617, 600

- Gibson, S., Fan, Y., and Toeroek, T., 2005a, ISSI publications, *submitted*
- Gibson, S., Foster, D., Burkepile, J., de Toma, G., Stanger, A.,2005b, *submitted for internal HAO review*
- Leka, K. D., Fan, Y., and Barnes, G., 2005, ApJ, 626, 1091
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Interactions:

a) Participation/presentations at meetings etc.

1. June 2-6, 2002: American Astronomical Association/Solar Physics Division meeting, Albuquerque, New Mexico, **poster**: *Magnetic flux ropes: would we know one if we saw one?,* **S. E. Gibson**, B. C. Low, K. D. Leka, Y. Fan, and L. Fletcher
2. June 10-15, 2002: IAU colloquium 188, Magnetic Coupling in the Solar Atmosphere, Santorini, Greece, **contributed talk** and conference proceedings paper: *Magnetic flux ropes: would we know one if we saw one?*, **S. E. Gibson**, B. C. Low, K. D. Leka, Y. Fan, and L. Fletcher
3. June 25-27, 2002: **meeting with collaborators at UC Berkeley**
4. December, 2002, Fall AGU meeting; **poster** : *Twisted magnetic flux in the corona*, **S. Gibson**, Y. Fan, and B. C. Low
5. May, 2003, Boulder, Space Weather week; June, 2003, Maryland, Solar Physics Division meeting; July, 2003, Hawaii, SHINE meeting, **poster**: *Photospheric Magnetic Field Properties of Flaring vs. Flare-Quiet Active Regions. II: A Magnetic Charge Topology Model and Statistical Results*, **G. Barnes**, K. D. Leka & D. Longcope

6. June, 2003, Maryland: Solar Physics Division meeting; July, 2003, Hawaii: SHINE meeting, **poster**: *The Emergence of a Twisted Magnetic Flux Tube into a Pre-existing Coronal Arcade,* **Y. Fan**, S.E. Gibson, and G. Barnes
7. August, 2003, Boulder, **Magnetic Topologies workshop with collaborators**
8. October, 2003, 5th Solar-B science meeting, Tokyo, **invited review talk**: *Dynamics of emerging flux tubes*, **Y. Fan**
9. December, 2003, Fall AGU meeting, San Francisco, **poster** : *Observational consequences of a magnetic flux rope topology*, **S. Gibson**, G. Barnes, Y. Fan, G. Fisher, K. D. Leka, D. Longcope, C. Mandrini, and T. Metcalf
10. December, 2003, Fall AGU meeting, San Francisco, **poster** : *Eruption of a buoyantly emerging magnetic flux rope*, **W. Manchester**, Y. Fan, T. Gombosi, D. de Zeeuw, A. Sokolov, and G. Toth
11. January, 2004, Committee on Solar and Space Physics, Irvine, **invited talk**: *3-D and twisted – Emergence and eruption of magnetic flux on the sun*, **S. Gibson**
12. March, 2004, LWS meeting, Boulder, **poster** : *Observational consequences of a magnetic flux rope topology*, **S. Gibson**, G. Barnes, Y. Fan, G. Fisher, K. D. Leka, D. Longcope, C. Mandrini, and T. Metcalf
13. March, 2004, LWS meeting, Boulder, **contributed talk**: *Magnetic Charge Topology (MCT) analysis of NOAA AR8210, May 1, 1998*, **G. Barnes**, D. Longcope, and K. D. Leka
14. June, 2004, AAS meeting, Denver, **contributed talk**: *Numerical Simulations of 3D Coronal Magnetic Fields Resulting from the Emergence of Twisted Magnetic Flux Tubes*, **Y. Fan**, S. Gibson
15. June, 2004, AAS meeting, Denver, **invited talk**: *Twist and Flare: the role of helical magnetic structures in the solar corona*, **S. Gibson**, Y.Fan, C. Mandrini, G. Fisher, P. Demoulin
16. June, 2004, AAS meeting, Denver, **poster**: *Magnetic topology, flux emergence/reconnection and velocities from a magnetic charge topology model for NOAA active region 8210*, **G. Barnes**, D. Longcope, and K. D. Leka
17. July, 2004, SHINE meeting, Big Sky, **poster**: *An analysis of the July 2002 coronal cavity*, **D. Foster**, Gibson, Burkepile
18. July, 2004, SHINE meeting, Big Sky, **poster**: *Numerical simulations of coronal magnetic flux ropes*, **Y. Fan** and S. Gibson
19. July 2004, SHINE meeting, Big Sky, **poster**: *Quantifying the performance of coronal extrapolations: just because it looks good, is it?*, **G. Barnes**, K. D. Leka, and T. Metcalf
20. July, 2004, AOGS meeting, Singapore, **invited talk**: *Twist and Flare: the role of helical magnetic structures in the solar corona*, **S. Gibson**, Y.Fan, C. Mandrini, G. Fisher, P. Demoulin
21. July, 2004, Berkeley, **Observational Constraints workshop with collaborators**
22. September, 2004, SOHO 15, St. Andrews, Scotland, **contributed talk**: *Twist and Flare: the role of helical magnetic structures in the solar corona*, **S. Gibson**, Y.Fan, C. Mandrini, G. Fisher, P. Demoulin
23. December, 2004, RHESSI-SOHO-TRACE workshop, Sonoma, CA, **contributed talk**, *Twist, Kink, and Other Contortions -- or -- On the availability of sufficient*

twist in active regions to trigger the kink instability, **K. D. Leka**, Y. Fan & G. Barnes

24. April, 2005, ISSI, Berne, Switzerland, **invited review talk**, *The evolving sigmoid: evidence for magnetic flux ropes in the corona before, during, and after eruptions*, **S. Gibson,** Y. Fan, and T. Toeroek
25. April, 2005, **Y. Fan** attended the IPAM workshop on Grand Challenge Problem in Computational Astrophysics held at UCLA
26. May, 2005, AGU/SPD, New Orleans, LA, **Karen Harvey Prize Lecture**, *The calm before the storm: the link between quiescent cavities and CMEs*, **S. Gibson**
27. May, 2005, AGU/SPD, New Orleans, LA, **poster**, *CME onset due to loss of confinement of twisted magnetic flux ropes*, **Y. Fan** and S. Gibson
28. June, 2005, SOHO 15/Solar Wind 11, **invited talk**, *Evolution of twisted magnetic flux tubes emerging into the solar corona*, **Y. Fan**
29. July, 2005, SHINE, Keauhou, HI, **poster**, *The evolving sigmoid: evidence for magnetic flux ropes in the corona before, during, and after eruptions*, **S. Gibson,** Y. Fan, and T. Toeroek
30. July, 2005, SHINE, Keauhou, HI, **poster**, *Can Force-Free Extrapolations Reproduce the Coronal Magnetic Topology*, **Graham Barnes**, K.D. Leka, Mike Wheatland and Yuhong Fan

b) Consultative and advisory functions: N/A

c) Transitions: N/A

New discoveries: None

Honors/Awards: 2005 AAS/SPD Karen Harvey "awarded to Sarah Gibson for her research on the role of helical magnetic fields in the structure and dynamics of the solar corona."